Exploring a Black Body Source as an Absolute Radiometric Calibration Standard and Comparison with a NIST Traced Lamp Standard

Robert O. Green, Thomas Chrien, and Chuck Sarture
Jet Propulsion Laboratory, California Institute of Technology, Pasadena, California 91109

INTRODUCTION

Radiometric calibration of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS) is required for the scientific research and application objectives pursued with the spectroscopic measurements (Green et al., 1998). Specifically calibration is required for: inter-comparison of AVIRIS data measured at different locations and at different times; analysis of AVIRIS data with data measured by other instruments; and analysis of AVIRIS data in conjunction with computer models. The primary effect of radiometric calibration is conversion of AVIRIS instrument response values (digitized numbers, or DN) to units of absolute radiance (Green et al., 1991). For example, Figure 1 shows the instrument response spectrum measured by AVIRIS over a portion of Rogers Dry Lake, California, and Figure 2 shows the same spectrum calibrated to radiance. Only the calibrated spectrum may be quantitatively analyzed for science research and application objectives.

Since the initial development of the AVIRIS instrument-radiometric calibration has been based upon a 1000-W irradiance lamp with a calibration traced to the National Institute of Standards and Technology (NIST) (Chrien et al., 1990, 1995, 1996, 2000). There are several advantages to this irradiance-lamp calibration approach. First, the considerable effort of NIST backs up the calibration. Second, by changing the distance to the lamp, the output can closely span the radiance levels measured by AVIRIS. Third, this type of standard is widely used. Fourth, these calibrated lamps are comparatively inexpensive. Conversely, there are several disadvantages to this approach as well. First, the lamp is not a primary standard. Second, the lamp output characteristics may change in an unknown manner through time. Third, it is difficult to assess, constrain, or improve the calibration uncertainty delivered with the lamp. In an attempt to explore the effect and potentially address some of these disadvantages a set of analyses and measurements comparing an irradiance lamp with a black-body source have been completed. This research is ongoing, and the current set of measurements, analyses, and results are presented in this paper.

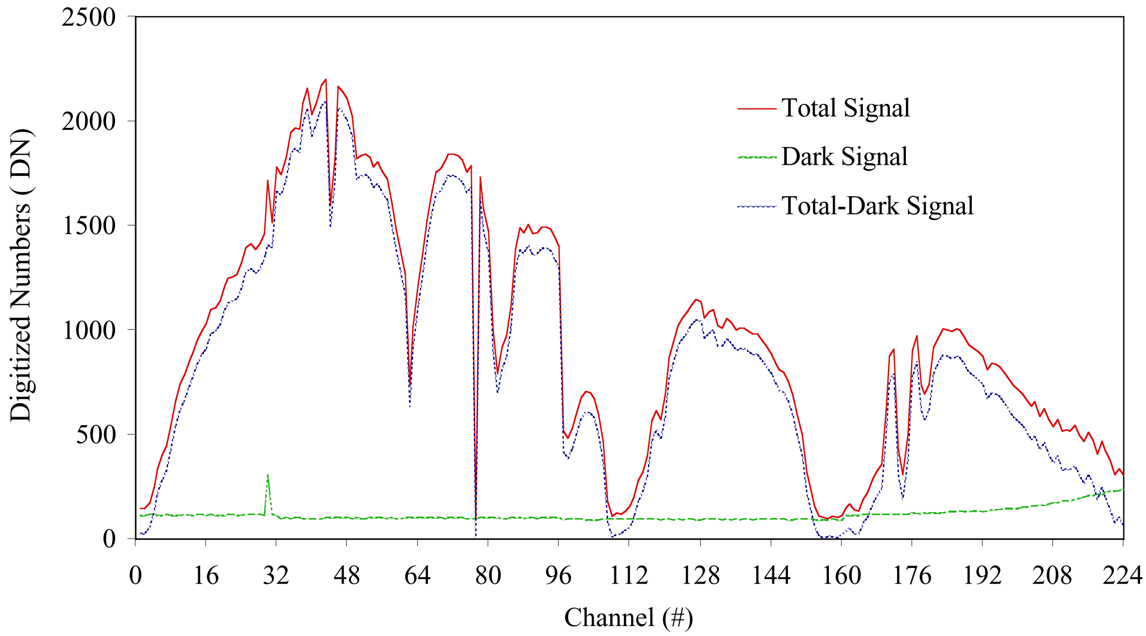

Figure 1. AVIRIS uncalibrated instrument response for a spectrum acquired over Rogers Dry Lake, California. The dark signal and instrument response with dark signal subtracted are shown as well.

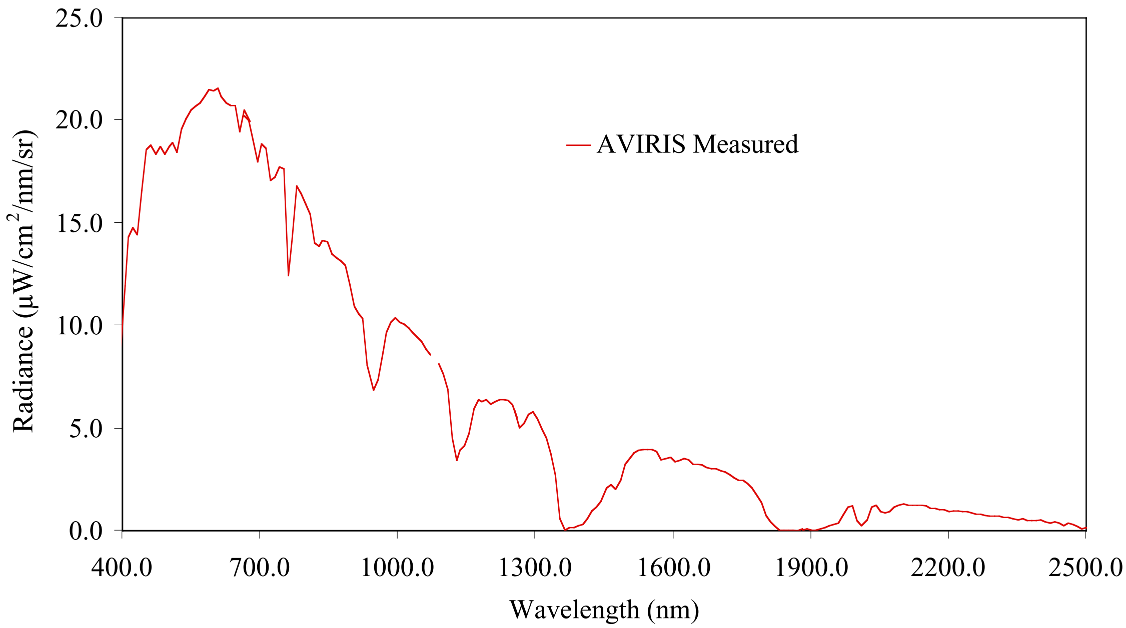

Figure 2. AVIRIS calibrated radiance from a spectrum acquired over Rogers Dry Lake, California.

LAMP RADIOMETRIC STANDARD

AVIRIS radiometric calibration is based on an irradiance standard lamp and a calibrated reflectance panel. The lamp is a 1000-W quartz-halogen tungsten coiled-coil filament lamp purchased from Optronics Laboratories, Inc. The irradiance lamp is held a known distance (nominally 500 mm) from the panel in a fixture with baffles to reject scattered light. For radiometric calibration this fixture is positioned such that AVIRIS views the panel at 45 degrees inclination. The AVIRIS instrument response output is calibrated with respect to the NIST traced radiance of the illuminated panel. Factors of the panel bidirectional reflectance distribution function (BRDF), as well as variation of lamp distance and angle from the panel, are calculated for the projected AVIRIS aperture. These factors are applied as part of the absolute radiometric calibration calculation. This approach eliminates the need for an integrating sphere and the transfer of a radiometric calibration to the integrating sphere. Figure 3 shows a diagram of the AVIRIS radiometric calibration fixture with standard lamp and reflectance panel. The primary factor in the absolute accuracy of the AVIRIS laboratory calibration is the accuracy of the irradiance standard lamp. A spectrum of the irradiance and uncertainty for the standard lamp (S-912) used in the year 1999 calibration of AVIRIS is given in Figure 4. The uncertainty varies from near 1 percent to greater than 6 percent in the AVIRIS spectral range from 400 to 2500 nm. Both the irradiance values and interpolated irradiance values are those provided with the lamp. The uncertainty values are those provided with the lamp. The interpolated uncertainty values have been calculated with a cubic spline algorithm (Press et al., 1988). To first order the spectral form of the irradiance lamp output appears to follow that of a Planck function (Liou, 1980). To explore aspects of this lamp calibration standard, the lamp was compared and analyzed with respect to Planck function calculations as well as a black body radiometric source.

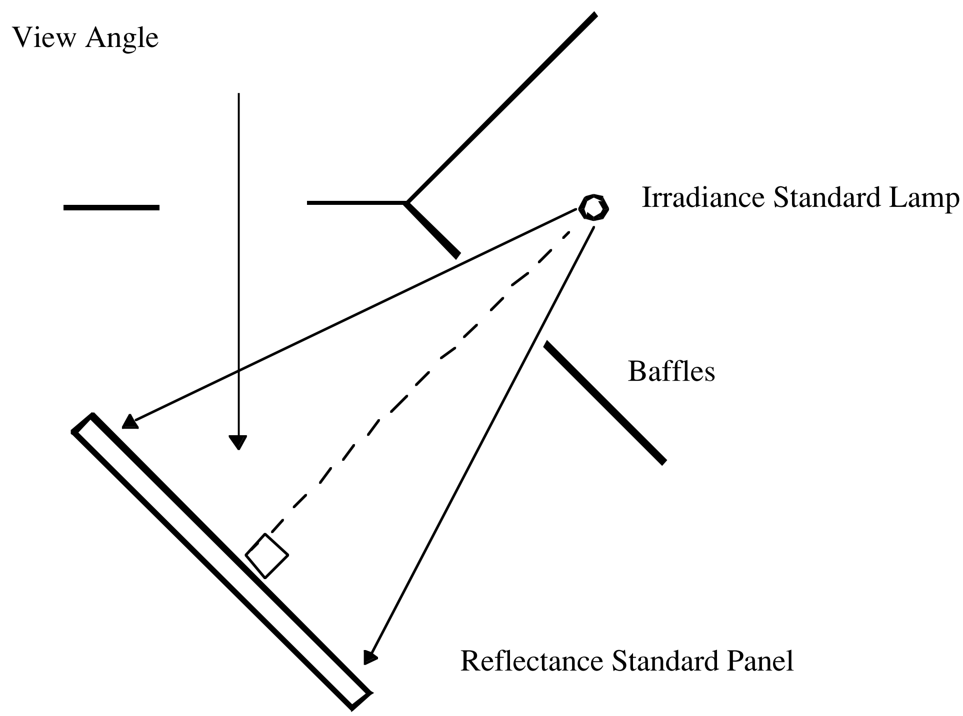

Figure 3. AVIRIS radiometric calibration fixture with irradiance lamp standard and reflectance standard panel.

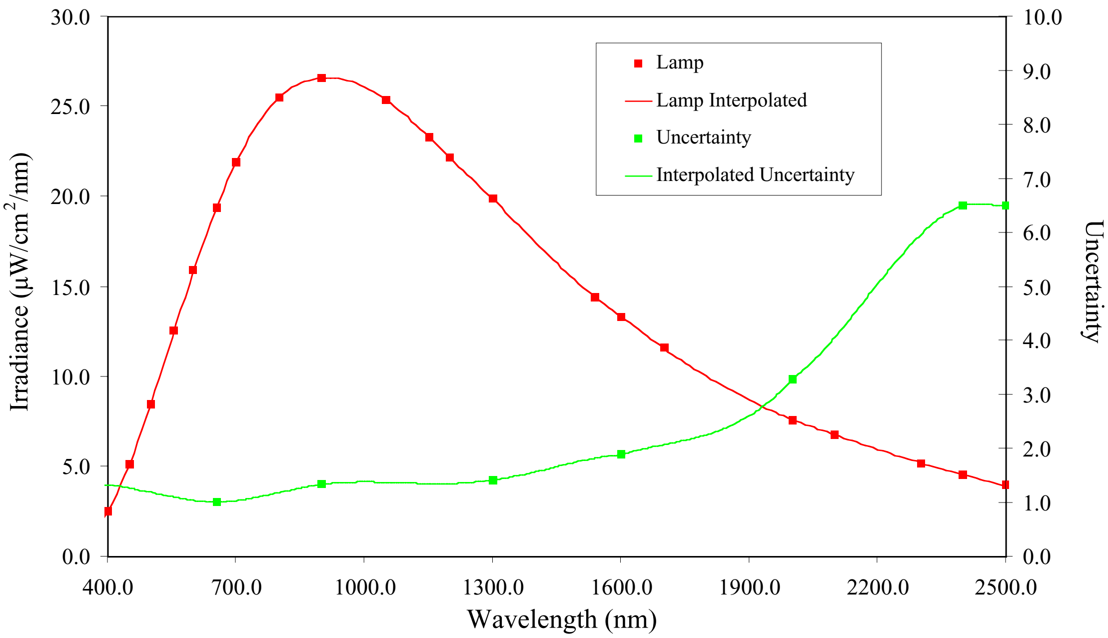

Figure 4. Calibration lamp irradiance at 500 mm distance with uncertainty traced to NIST. The lamp, lamp interpolated, and uncertainty values are given as delivered with the lamp. The interpolated uncertainty values were calculated with a cubic spline function.

CAVITY BLACK BODY SOURCES

The radiance from a cavity black body may be calculated with the temperature, the emissivity, and the Planck function. A high temperature cavity black body offers potential as a primary absolute radiometric calibration standard that may be used for the calibration of AVIRIS as well as to explore the lamp irradiance uncertainty. Figure 5 shows the spectral distribution of radiance from a cavity black body at temperatures of 3000, 2000, and 1000 K. The radiance magnitude has been scaled to a value of 100 at the peak. To calculate the radiance output of any cavity black body, accurate knowledge of the temperature is required. For a high temperature black body, there is feedback on the accuracy of the temperature based on the peak of the black body curve. The relationship between temperature and radiance peak is given by Wien's displacement law (Liou, 1980). With a good relative spectral measurement of the black body output the temperature may be validated and potentially determined directly. With knowledge of the temperature and emissivity, the radiance of the cavity black body may be calculated directly with the Planck function. The cavity black body may then be used as a primary absolute radiometric calibration standard. AVIRIS has access to a high temperature cavity black body with a range from 1000 to 3000 K built by Electro Optical Industries, Inc. The emissivity of the cavity is better than 0.99. For practical use, precision apertures are required to bring the output of the high temperature source into the range of AVIRIS measurements. Research is ongoing for the use of the high temperature cavity black body for the calibration of AVIRIS.

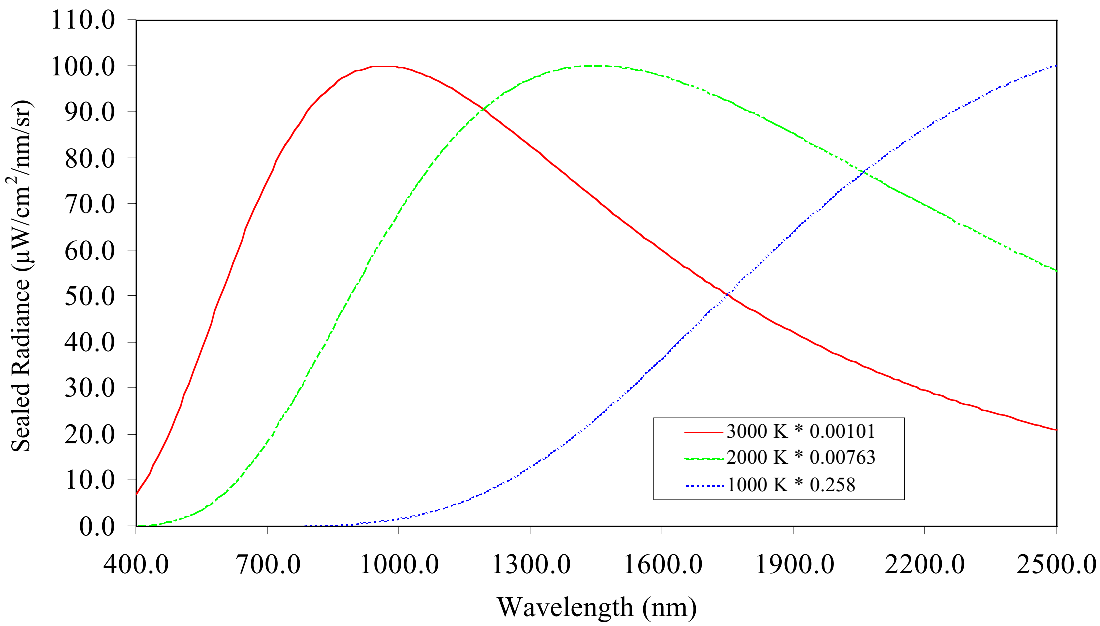

Figure 5. Planck functions for a cavity black body at different temperatures. The data are scaled to a peak value of 100. The scaling factors are 0.00101, 0.00763, and 0.258 for the 3000, 2000, and 1000-K spectra, respectively.

COMPARISON OF THE IRRADIANCE LAMP TO A PLANCK FUNCTION

To a first order the calculated Planck function for a 3000-K cavity black body resembles the form of the calibration curve for the irradiance lamp standard. A simple analysis was performed to explore how well the irradiance lamp output could be modeled by a Planck Function. Initially a spectral fitting approach was used to match a single temperature Planck function with fractional fill parameter to the irradiance calibration of the lamp. The fractional fill parameter accounts for geometric and distance factors as well as spectrally uniform variations in the emissivity of tungsten and the lamp quartz envelope. A model with two temperatures and fractional fill parameters provided a better fit, though only over the spectral range from 1000 to 2500 nm. Figure 6 shows the achieved fit between the irradiance lamp calibration and a two-temperature Planck function model. Temperatures of 3425 K and 511 K were required in the model with a fractional fill of 0.000148 and 0.0054 respectively. The percent difference between the irradiance lamp calibration and the two-temperature Planck function model shows spectral variation ranging from +2 to –4 percent in the range from 1000 to 2500 nm. This spectral variation could be due to tungsten emissivity, interpolation errors, or other factors. This variation may also be an indication of the spectral form of the uncertainty in the lamp calibration. Insight into the spectral form of the uncertainty in the irradiance lamp output is the objective of this research and is critical to improving the absolute radiometric calibration of AVIRIS.

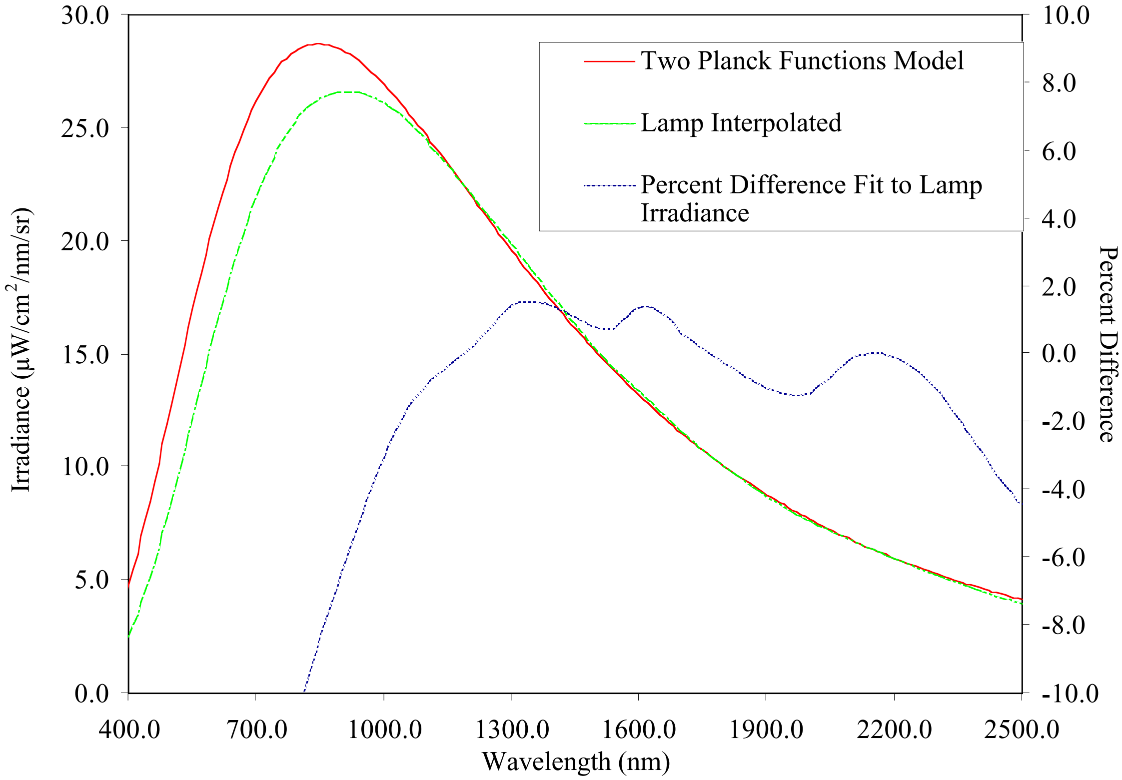

Figure 6. Results of fit between lamp irradiance and two-temperature Plank function calculations plus a fractional fill factor over the range from 1000 to 2500 nm.

MEASURED BLACK BODY AND THE IRRADIANCE LAMP

In addition to exploring a simple Planck function model for the irradiance lamp spectral output, spectral measurements were made comparing the output of a moderate-temperature cavity black body with the output of the irradiance lamp standard. Figure 7 shows the calculated output of an 820-K cavity black body source in the AVIRIS calibration laboratory. This source was measured by a portable spectrometer that covers the spectral range from 350 to 2500 nm at nominally 10 nm intervals with 1 nm output sampling. Figure 8 show the spectrometer output from the 820-K black body source as well as the measured output for AVIRIS calibration fixture with the NIST traced irradiance lamp and calibrated panel. From these measurements, usable signal levels were obtained for both sources over the spectral range from 1000 to 2500 nm. The radiance from AVIRIS calibration fixture and these portable spectrometer measurements were used to predict the radiance output of the 820-K black body source. The predicted radiance is shown in Figure 9. The shape of the predicted radiance spectrum conforms to that expected for a cavity black body. The low measured signal level for the lamp source at the long wavelength end of the spectrum induces increased noise and uncertainty near 2500 nm. A comparison of the AVIRIS calibration-fixture derived radiance and the Planck function calculated radiance is given in Figure 10. Over the spectral range from 1000 to 2500 nm the agreement is good. The percent difference curve shows the areas of disagreement. In the 1400 and 1900 nm spectral regions there are some disagreements because there was a longer path and more water vapor in the calibration fixture measurement than the black body measurement. The low signal level effects of the lamp measurement at 2500 nm are also apparent. In the spectral range from 1200 to 2400 nm, the spectral variation of the percent difference ranges from +2 to –4 percent. This is similar to the range of expected uncertainty values delivered with the NIST traced lamp is from 2 to 6 percent in this spectral region. It is reassuring the NIST traced AVIRIS calibration fixture can predict the radiance of the 820-K cavity black body to this level of accuracy.

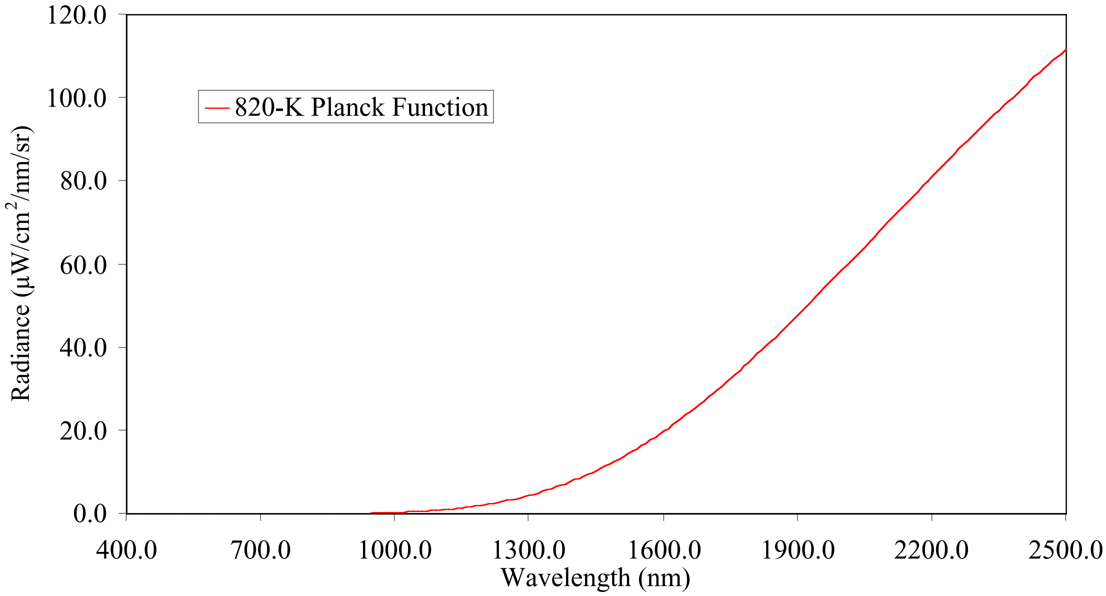

Figure 7. Planck function calculation for 820-K black body source in the AVIRIS calibration laboratory.

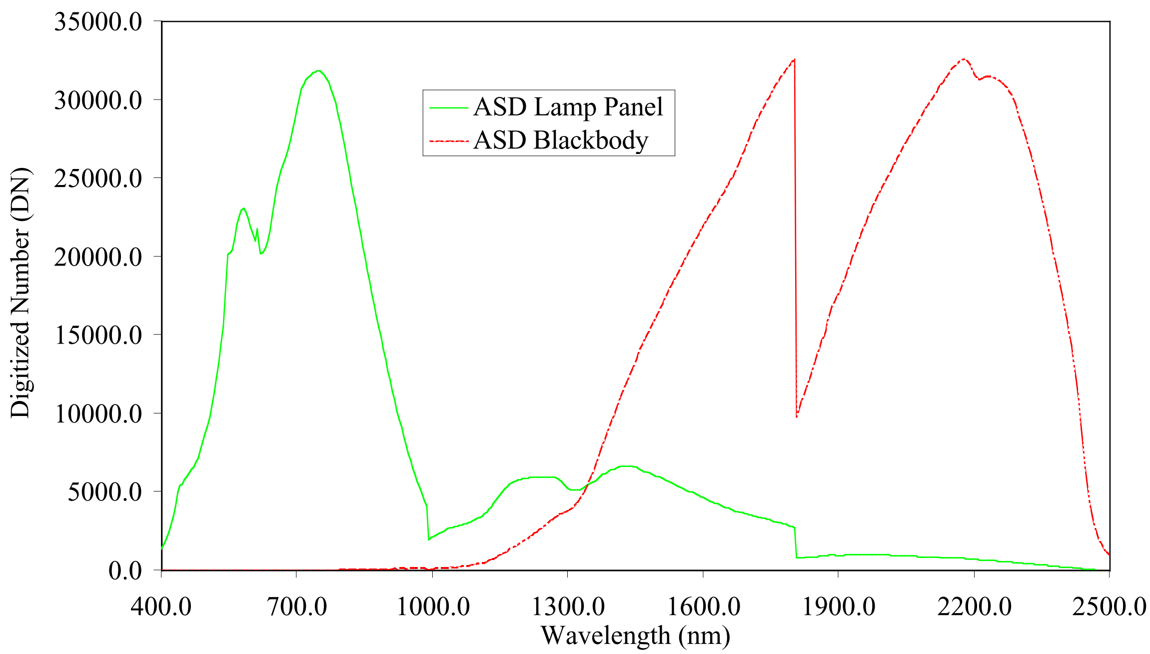

Figure 8. Spectrometer measurement of lamp panel source and 820-K black body source.

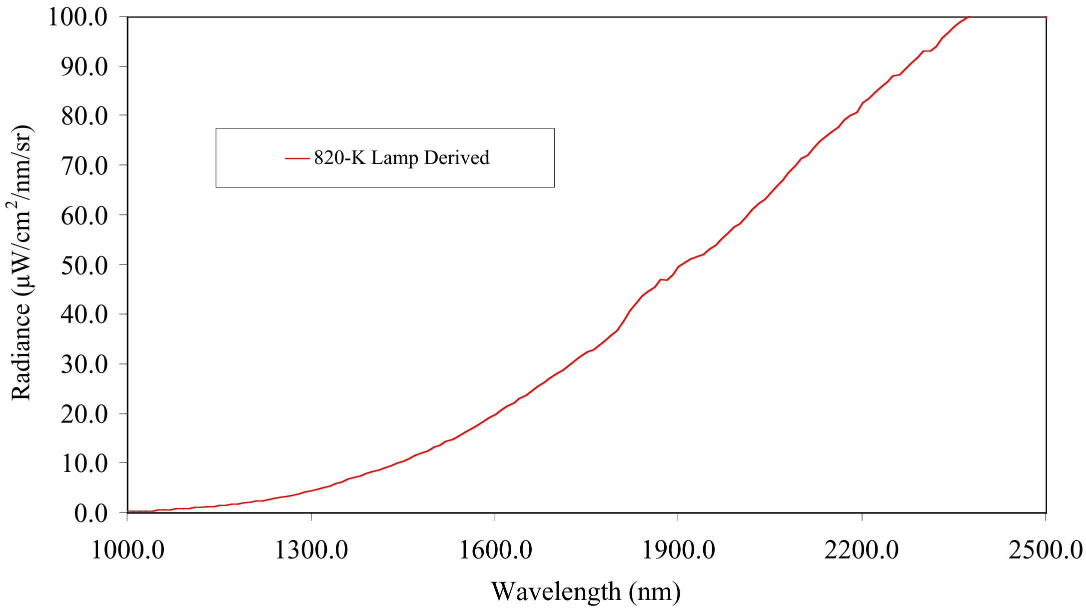

Figure 9. Predicted radiance from 820-K black body based on lamp panel calibration.

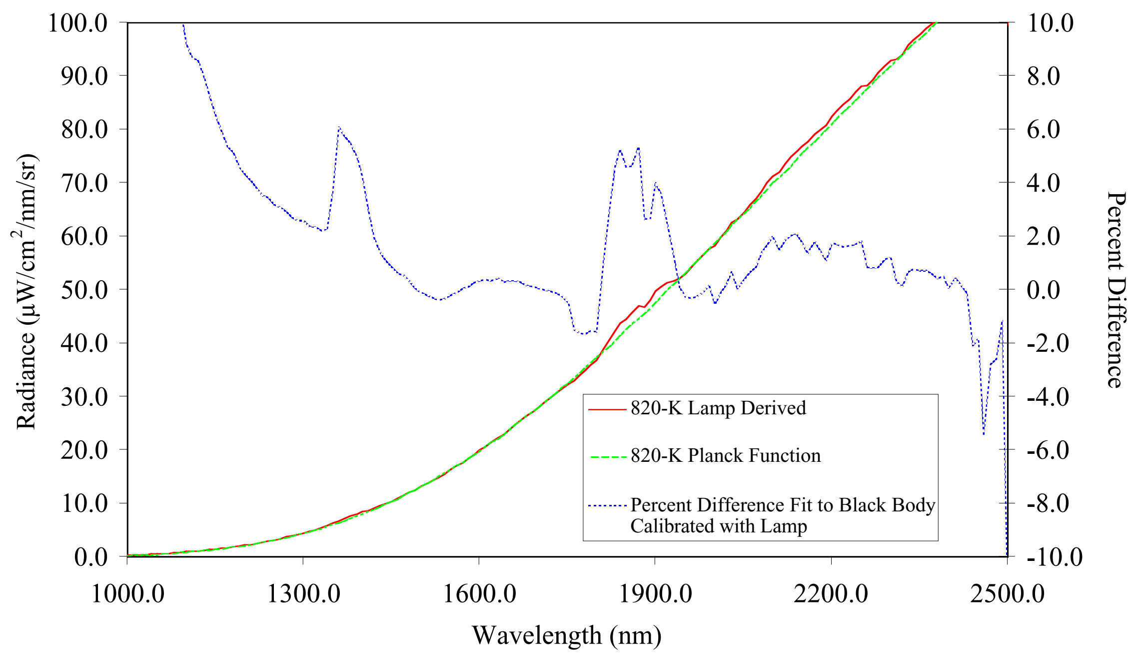

Figure 10. Comparison of 820-K Planck function calculation and lamp based predicted irradiance from 820 K black body source. The percent difference is shown as well.

In the range from 1200 to 2500 nm, the cavity black body measurement based percent difference is of a similar form and magnitude to that found in the comparison of the two-temperature Planck function model and the irradiance lamp calibration. Figure 11 shows these two spectral percent difference results. The similarity suggests this spectral form may represent the uncertainty in the irradiance lamp calibration.

The source of this spectral variation is likely a combination of irradiance lamp calibration uncertainty and uncertainty introduced in the interpolation to a continuous spectrum. The interpolated data analyzed here are those provided with the NIST traced lamp. Interpolation is a required step for calibration of any instrument operating in this spectral range. Only the interpolated spectral radiometric source can be convolved to the spectral response functions of the remote sensing instrument. This uncertainty is relevant for AVIRIS and other instruments measuring in this spectral range and using irradiance lamp based calibration. Improved understanding the uncertainty of the radiometric calibration of the NIST traced lamp was a primary objective of this effort. This understanding in conjunction with cavity black body source will support development of a strategy for an improved radiometric calibration of AVIRIS.

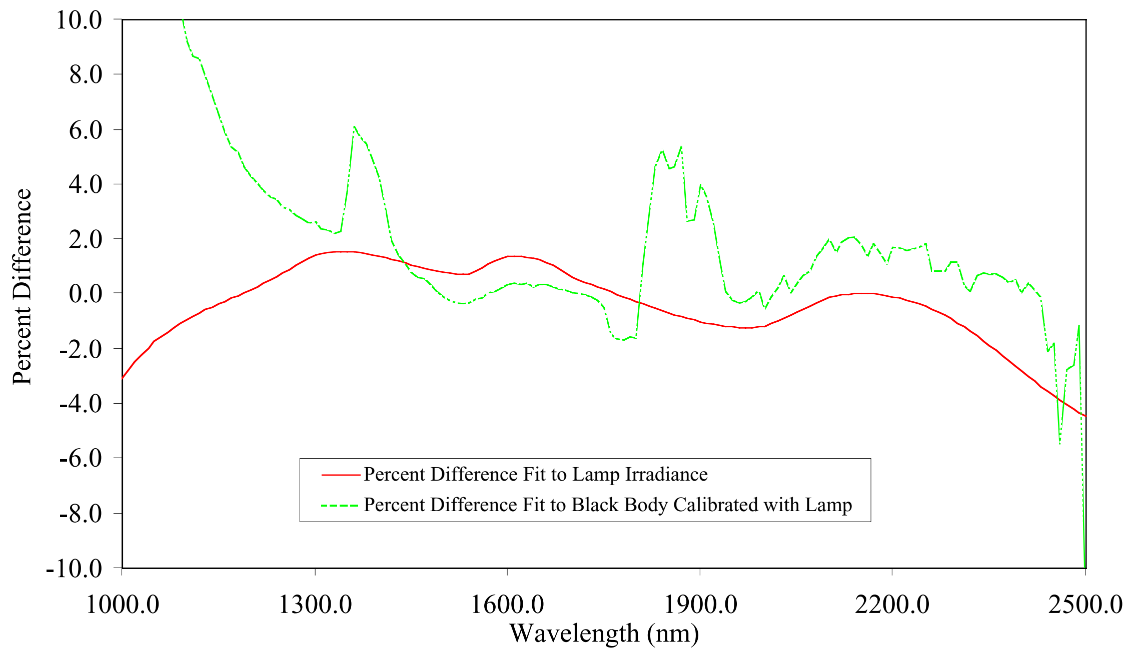

Figure 11. Comparison of percent difference from Planck function fit to lamp irradiance with percent difference from 820-K Planck function and 820-K black body source calibrated with lamp panel standard.

CONCLUSION

Radiometric calibration of AVIRIS data is required for quantitative use of the AVIRIS spectral measurements for Earth science research and application objectives. From the time of the first AVIRIS flights the instrument as been calibrated based on irradiance lamp standards. The standard lamp approach has both advantages and disadvantages. Important disadvantages are the user does not control the primary radiometric standard and the user is limited to the calibration uncertainty of the lamp. The research presented here explores the properties of the AVIRIS irradiance lamp based calibration standard with respect to a Planck function model and cavity black body measurements over the range from 1000 to 2500 nm.

A simple two-temperature Planck function model with fractional fills provides a good fit in the spectral range from 1000 to 2500 nm using the interpolated calibration irradiance values delivered with the standard lamp. In detail the percent difference between the model and lamp show some spectral variation in the range from +2 to –4 percent. This percent difference is consistent with the calibration uncertainty delivered with the standards lamp. With the goal to continue to improve AVIRIS absolute radiometric calibration it is necessary to understand and improve upon the radiometric calibration uncertainty of the NIST traced irradiance lamps.

The measurements and analysis of the 820-K laboratory cavity black body suggests that this source may be a viable absolute radiometric calibration standard over the range from 1000 to 2500 nm. Even if not used as a source, the black body measurements provide a check of the calibration delivered with the NIST traced irradiance lamp. A higher temperature source will be required to calibrate the spectral range from 400 to 1000 nm. Work has begun experimenting with a 3000-K black body source for this objective. An advantage of a high temperature black body is that the temperature may be determined by the spectral location of the peak radiance output. This temperature may in turn be used to validate and improve the calibrated output of the cavity black body source. The AVIRIS calibration laboratory currently has access to a high temperature black body source. This offers the potential to have a new primary radiometric calibration standard in the AVIRIS laboratory and to improve upon the uncertainty of the irradiance lamp calibration approach. The overall objective of this work is to move AVIRIS radiometric calibration toward the 1 percent absolute accuracy.

REFERENCES

Chrien, T. G., R. O. Green, and M. L. Eastwood, "Accuracy of the spectral and radiometric laboratory calibration of the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)," *SPIE Vol. 1298, Imaging spectroscopy of the terrestrial environment*, G. Vane, ed., pp. 37–49, 1990.

Chrien, T. G., R. O. Green, C. Chovit, M. Eastwood, J. Faust, P. Hajek, H. Johnson, H. I. Novack, and C. Sarture, "New Calibration Techniques for the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS), 1995," *Proc. Fifth Annual Airborne Earth Science Workshop*, JPL Pub. 95-1, Jet Propulsion Laboratory, Pasadena, California, pp. 33–34, 1995.

Chrien, T. G., R. O. Green, C. J. Chovit, M. L. Eastwood, and C. M. Sarture, "Calibration of the Airborne Visible/Infrared Imaging Spectrometer in the Laboratory," *Proc. Sixth Annual Airborne Earth Science Workshop*, JPL Pub. 96-4, Vol. 1, Jet Propulsion Laboratory, Pasadena, California, pp. 39–48, March 3–5, 1996.

Chrien, T. G., R. O. Green, B. Pavri, and J. Wall, "Calibration Validation of the AVIRIS Portable Radiance Standard," *Proc. Ninth Airborne Earth Science Workshop*, JPL Pub. 00-18, Jet Propulsion Laboratory, Pasadena, California, pp. 101–110, 2000.

Green, R. O., S. A. Larson, I. Novack, "Calibration of AVIRIS Digitized Data," *Proceedings of the Third AVIRIS Workshop*, JPL-Pub 91-28, Jet Propulsion Laboratory, Pasadena, California, pp. 109–118, 1991.

Green, R. O., M. L. Eastwood, C. M. Sarture, T. G. Chrien, M. Aronsson, B. J. Chippendale, J. A. Faust, B. E. Pavri. C. J. Chovit, M. Solis, M. R. Olah, and Q. Williams, "Imaging spectroscopy and the Airborne Visible/Infrared Imaging Spectrometer (AVIRIS)," *Remote Sens Environ* 65: (3) 227–248, Sept. 1998.

Liou, K. N., *An Introduction to Atmospheric Radiation*, Academic Press, Inc., New York, pp. 392, 1980.

Press, W. H., S. A. Teukolsky, W. T. Vetterling, and B. P. Flannery, *Numerical Recipes in C*, Cambridge University Press, pp. 994, 1988.

ACKNOWLEDGMENT

The research described in this paper was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration.

Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not constitute or imply its endorsement by the United States Government or the Jet Propulsion Laboratory, California Institute of Technology.